Scientific Objective 1: Global Flow of Water Vapor and Pollutants

The purpose of scientific objective 1 is to trace the global flow of water vapor and pollutants in the troposphere and lower stratosphere.

Introduction

Understanding atmospheric transport processes requires understanding the transformation and flow of water vapor and pollutants from local chemical and microphysical processes through the general circulation of the atmosphere itself. In recent years, the atmosphere has increasingly been viewed as one of our natural resources, and the possibility that it would suffer from contamination by anthropogenic pollutants has increased our interest in the transport of such impurities over long distances by atmospheric motions. The understanding of transport processes is therefore of vital interest, not only for local air pollution control and planning but also for studies of global contamination of the atmosphere by widespread application of fertilizers, by the use of CFM's in aerosol spray cans, by nuclear experiments, by aviation, and by space technology.

The use of trace constituents of the atmosphere for establishing the effects of the general circulation on the transport of pollutants has been actively pursued. The global nature of the problem, however, requires new approaches to augment our understanding of global transport processes in the atmosphere and of the general circulation, especially outside and above the radiosonde networks. In particular, it appears possible to use a lidar on Shuttle or some other spacecraft to trace the global motion of particulates and gaseous pollutants which react only slowly with the surrounding constituents of the atmosphere or with the Earth's surface and which are generated in specific source regions. Ground-based lidars have already been used, for example, to document the time history of the changes in the height and concentration of aerosol particles in the stratosphere after the eruption of the Mt. Agung volcano in Bali in 1963 and after the eruption of the Fuego volcano in 1975. These observations, made at various times and locations by a number of different lidar groups, have been used to study stratospheric transport processes (e.g., Cadle et al., 1976). It would be extremely interesting to carry out a similar series of global observations of stratospheric aerosols from Shuttle for a 2- or 3-year period when another major volcanic eruption occurs. It is not necessary, of course, to wait for dramatic natural events such as a large volcanic eruption to study atmospheric transport processes. Measurements of dust particles transported in distinct layers over large distances from desert regions in Africa and Asia would provide data for use in studying tropospheric transport processes. Also, measurements of aerosol particles or gaseous pollutants such as O_3, SO_2, or the CFM's downwind of major urban areas could be used as input for testing and validating models of atmospheric dispersion by mesoscale flow fields.

There are a number of other problems that are of current interest in the scientific community. One is that of understanding the mechanisms for troposphere-stratosphere exchange processes involving such phenomena as the intrusion of ozone from the stratosphere to the troposphere in extremely thin (e.g., 1/2 km) layers or the injection into the stratosphere of tropospheric

air with relatively high concentrations of water vapor in the vicinity of thunderstorms (Kuhn et al., 1971). Another subject having considerable current interest is that of atmospheric CO_2. The increase in the CO_2 content of the atmosphere has been well documented since 1958; however, the increase is equivalent to only about 50 percent of that known to have been produced by fossil fuel burning during the same period. Controversy exists on the process responsible for removing the excess CO_2. Accurate measurements of the concentration (or mixing ratio) of CO_2 near the Earth's surface might help to identify important sources and sinks of the molecule and thereby contribute to a resolution of that debate.

Previous Lidar Research

The presence of aerosol layers near or below the mesopause has been established by numerous visual observations of noctilucent clouds. Lidar measurements have been conducted at high latitudes where noctilucent clouds are observed (Fiocco and Grams, 1966 and 1969). The measurements indicate that the altitude region between 60 and 70 km contains an appreciable amount of particulate material during periods of noctilucent cloud activity; observations of transient features of a noctilucent cloud were also obtained during those experiments. Lidars have also detected mesospheric scattering layers at lower latitudes. During October and November of 1966 in England, Bain and Sandford (1966) detected layers at about 71 km with scattering 2.5 times that expected from a molecular atmosphere. McCormick et al. (1967) observed echoes from the 65 to 85 km region during February 1967 in Maryland. Latitudinal and seasonal changes in the vertical distribution of extraterrestrial aerosols below 100 km have been related to the general circulation of the upper atmosphere (Fiocco and Grams, 1971). The aerosol layers observed near 70 km are presumably of extraterrestrial origin. Estimates of the mass flux of extraterrestrial dust based on lidar data obtained at high latitudes (Fiocco and Grams, 1969) are in agreement with results obtained by other techniques (summarized, for example, by Parkin and Tilles, 1968).

The layer of aerosols found in the interval from about 15 to 25 km has also been observed extensively by Lidar. The existence of the layer was confirmed in the early 1960's by Junge and his collaborators (Junge and Manson, 1961; Chagnon and Junge, 1961; Junge et al., 1961) using balloon-borne impactors. Gruner and Kleinert (1927) and Gruner (1942) had previously concluded from twilight observations that there was dust above the tropopause, as had Bigg (1956) and Volz and Goody (1962) from more sophisticated twilight sky intensity measurements. The "Junge layer" has since been verified and studied extensively by many investigators employing both in situ and remote sensing techniques. The first lidar observations of the layer were reported by Fiocco and Grams (1964). These investigators carried out a 2-year study of the layer in 1964-65 in Massachusetts (Grams and Fiocco, 1967). The lidar profiles indicated a layer in the 15 to 20 km region for which the backscattering was almost twice as large as that expected from a dust-free molecular atmosphere; i.e., the backscattering from the aerosols and molecules was approximately equal. Comparisons between these results and those obtained earlier by other techniques indicated that the stratospheric aerosol concentration was about one order of magnitude higher, presumably because of the eruption of Mt. Agung in March 1963.

Since then, other investigators have used lidars for stratospheric aerosol studies. These results indicate a long-term trend toward decreasing aerosol concentrations after the Mt. Agung eruption which continued until late 1974, when high backscattering ratios were again observed following the eruption of the Fuego volcano. The temporal variation of the lidar returns from the stratospheric aerosol layer is summarized in figure 1. Results obtained with balloon-borne photoelectric particle counters are also shown for comparison. The lidar results shown in figure 1 appear to bracket the natural variability of the backscattering cross section of the stratospheric aerosol, with the exception of times and locations very close to volcanic injections.

The trapping of aerosol particles below temperature inversions is an effect that can be detected by lidar and used in boundary-layer studies. For example, a vertically pointing laser radar operated at a fixed location to determine time-height data on aerosol concentration can define the height of the boundary layer continuously throughout the diurnal cycle, as demonstrated by Uthe (1972) and Russell et al. (1974) and illustrated in figure 2. Alternatively, spatial variations of boundary-layer height have been obtained with a ground-based scanning lidar measuring two- or three-dimensional aerosol concentration profiles (Collis, 1969; Olsson et al., 1974) and with an airborne lidar looking downward (Grams et al., 1975; Melfi et al., 1974), as illustrated in figure 3. Lidar applications involving the acquisition of data on pollutant particles have been discussed by a number of authors, including Johnson (1969 and 1971), Barrett and Ben-Dov (1967), Hamilton (1966, 1967, and 1969), and Ruppersberg and Renger (1976).

Shuttle Studies

The above discussion underlines the fact that lidar observations of aerosol layers in the atmosphere are of considerable scientific interest. While many of the reported studies were obtained with ground-based systems, a number of experiments using airborne lidars have also been carried out. These studies reflect an interest in using lidars for mapping the spatial distribution of the airborne particles over large geographic areas to study, for example, the dispersion of pollution particles in the urban boundary layer (Melfi et al., 1974) or the meridional distribution of particulates in the stratospheric aerosol layer (Fox et al., 1973). It is apparent that the ability of the Shuttle lidar to detect and trace the global flow of aerosol particles in the mesosphere, stratosphere, and troposphere will attract the interest of the scientific community. While other satellite techniques can obtain data above the tropopause (e.g., the SAM II or SAGE solar occultation measurements), the ability of an active lidar system to operate continuously along the Shuttle orbit provides a unique ability to obtain high-resolution horizontal aerosol data for use in models of aerosol transport. Furthermore, lidar represents the only technique available for studying aerosol vertical distributions in the troposphere from an orbiting platform. Table I summarizes the parameters to be measured for experiments to trace the global flow of pollutants. The table lists the accuracies and resolutions required for each measurement.

Large-scale transport of atmospheric aerosol layers.- In considering the use of the Shuttle lidar for studies of aerosol transport, it is noteworthy

that there are a number of interesting research topics associated with aerosol particles generated in specific source regions and transported in distinct layers for distances measured in thousands of kilometers. The most notable examples in the troposphere are the dust layers generated in vast desert regions such as the Saharan desert in Africa and the Takla Makan and Gobi deserts of eastern Asia. In the stratosphere, as discussed earlier, large amounts of volcanic ash and gases can be injected by violent volcanic eruption; the ash and particles formed from gases such as SO_2 or COS are then dispersed by atmospheric transport processes over the entire globe.

The existence of lidar data on the temporal and spatial distribution of stratospheric aerosol particles after the eruption of the Mt. Agung and Fuego volcanos has already led to quantitative studies of the dispersion in the stratosphere. Cadle et al. (1976) used lidar data obtained over a 2-year period in Massachusetts (Grams and Fiocco, 1967) after the eruption of Mt. Agung to test a two-dimensional stratospheric transport model. Figure 4 (from Cadle et al., 1976) shows a comparison between predicted aerosol concentrations at 18 km altitude and the corresponding temporal variation of concentration determined from lidar observations after the Mt. Agung eruption. Figure 5 shows the meridional distribution of stratospheric aerosol particles at various times after the Mt. Agung eruption as predicted by the model of Cadle and his colleagues.

Dust layers from the Saharan and Asian deserts are interesting examples of cases for testing models for long-range transport of particulates in the troposphere. One of the most striking examples of long-range transport of atmospheric particulates is the layer of particles observed over the northern tropical Atlantic Ocean during the summer months. The major fraction of the aerosols in this layer is composed of mineral particles originating in the arid and semiarid regions of West Africa (Savoie and Prospero, 1977) and transported into the oceanic area in large-scale Saharan air outbreaks (Prospero and Carlson, 1972). These massive outbreaks are known to carry large amounts of dust from the west coast of Africa to the Caribbean (Prospero et al., 1970). Figure 6 shows a vertical profile of the aerosol concentration as measured by Kondratyev et al. (1976) with aerosol-particle counters operated on an aircraft over the Atlantic during the GATE program in summer 1974. The Saharan dust layer is typically several kilometers thick, with the base of the dust layer located some 1 to 1.5 km above the ocean surface. The high concentrations of dust in the layer cause considerable attenuation of solar radiation, with the optical thickness often exceeding unity. The dust cloud significantly increases the albedo of the Earth atmosphere system, and the Saharan dust outbreaks are clearly visible in satellite photographs as large bright areas over the ocean with horizontal dimensions often greater than 1000 km. Such layers would easily be detected by the Shuttle lidar and, along with photographic images from geosynchronous satellites, would significantly increase our ability to understand long-range transport processes by mapping the vertical and horizontal dispersion of the dust layer as it moves across the Atlantic.

Recently, Rahn et al. (1977) suggested that some Arctic haze layers were, in fact, dust layers transported over long distances (9000 to 12 000 km) from the Takla Makan and Gobi deserts in eastern Asia. The term "Arctic haze" refers to turbid layers of air found regularly over the pack ice north of Alaska during

periods of clear weather. These layers are hundreds to thousands of kilometers wide, 1 to 3 km thick, and can occur as single or multiple bands of haze at nearly any level of the troposphere. Although they are generally difficult to detect visually from the ground, they can be viewed from aircraft since horizontal and slant visibilities within the layer can be as small as 3 to 8 km. An observation program involving the operation of surface stations and an air-borne sampling program by the Universities of Alaska and Rhode Island (Rahn et al., 1977), Shuttle lidar observations of the temporal variation in the vertical distribution and horizontal extent of the Arctic haze layers, and an appropriate three-dimensional transport modeling effort could form the basis for a comprehensive study of the transport of tropospheric dust over long distances.

Boundary-layer aerosol morphology.- Observing aerosol particles associated with smaller scales of atmospheric motion will require additional levels of sophistication for both the lidar system and the supporting modeling efforts. In particular, higher horizontal resolution would be desired for studies of mesoscale transport processes. Figure 7 shows the results of analyzing the surface visibility in the vicinity of St. Louis, Missouri, during the METROMEX program (Shea and Auer, 1978). It is apparent that studies of the downwind transport of urban pollution particles would be possible when horizontal measurements of high spatial resolution (e.g., 10 km) are available.

Sources and transport of tropospheric species.- The techniques described for studying aerosol transport can be applied to gaseous constituents when lidar techniques such as DIAL become operational. For example, ozone distributions display maximum concentration values downwind of pollution sources in urban areas. Figure 8 shows a mesoscale analysis of ozone concentration (in parts per billion by volume) in southern Ontario (Chung, 1977).

Quantification of transport models for tropospheric and stratospheric pollutants using wind and temperature measurements.- All the transport studies described above would have to rely on data obtained by other techniques such as analysis of data from the existing network of meteorological stations or special measurement programs carried out as part of a specific Shuttle experiment as input to the dispersion models. The spatial resolution of this data may not be adequate, especially over the oceans and other data-sparse regions. The transport studies will be able to take advantage of more sophisticated modeling efforts with a more complete set of data, including lidar temperature profiles and data on wind speed and direction as well as the lidar observations of the spatial and temporal distribution of the pollutant particles or gases.

Extension of pollutant transport models to include profiles of additional trace species.- New insight into the fate of atmospheric pollutants would follow from studies involving a number of atmospheric constituents that can react with each other during the transport process. Thus, simultaneous measurements of SO_2 concentrations and aerosol concentrations downwind of an extended urban source region may provide new information on the rate of conversion of SO_2 to sulfate particles. Studies of this type would necessarily require a considerable amount of confidence in the transport model, as well as the amount and quality of the concentration data used as input for predicting the long-range transport of aerosols and gases, before gas-to-particle conversion rates could be deduced.

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TABLE I.- PARAMETERS TO BE MEASURED TO TRACE GLOBAL FLOW OF POLLUTANTS

Parameter	Height range, km	Δx, km (a)	Δz, km (b)	Remarks	Lidar experiment
Aerosols	0 to 10	100	1	20 percent, haze layers, thin cirrus, Saharan and Asian dust	2, 3
	10 to 30	500	2	20 percent, stratospheric aerosols	6, 24
H_2O	0 to 10	100	1	20 percent	9, 10
	10 to 20	500	2	20 percent	
	Total	100	---	20 percent	
O_3	0 to 10	100	1	20 percent	10, 12
	10 to 30	500	2	20 percent	18, 17
XY: e.g., SO_2, CH_4, NH_3, NO_2, N_2O, CFM's, etc.	0 to 10	100	1	20 percent	10, 18, 23
	10 to 50	500	3	20 percent	
	Total	100	---	20 percent	
Temperature	0 to 3	100	0.2	1 K; define boundary layer	17
	5 to 20	500	1	2 K; define tropopause	
V_x	0 to 10	100	1	5 m/s	19, 20
	10 to 50	500	2	10 m/s	
V_z	0 to 10	100	1	5 cm/s	
	10 to 50	500	2	10 cm/s	
CO_2 mixing ratio	0 to 3	100	3	1 percent; identify sources and sinks	

[a]Horizontal resolution.
[b]Vertical resolution.

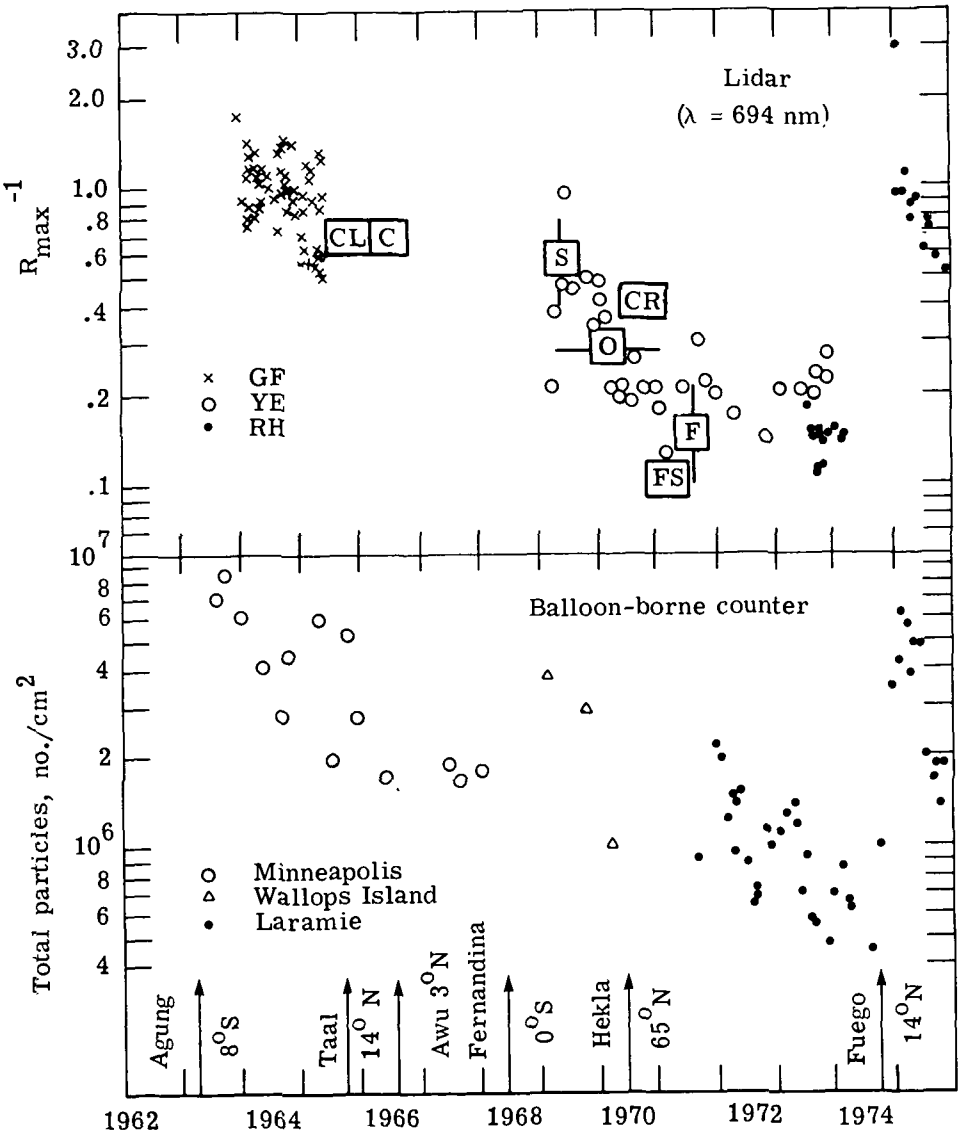

Figure 1.- Comparison of stratospheric aerosol measurements obtained by lidar and balloon-borne dustsondes between 1962 and 1975. Lidar observations obtained by:

GF (Grams and Fiocco), Mass.
CL (Collis and Ligda), Calif.
C (Clemesha et al.), Jamaica
CR (Grams and Rosen)
S (Schuster), Colo.
O (Ottway), Jamaica
FS (Frush and Schuster), Colo.
F (Fox et al.), Hawaii and Bermuda
YE (Young and Elford), Australia
RH (Russell and Hake)

(From Grams and Rosen, 1978, courtesy National Center for Atmospheric Research)

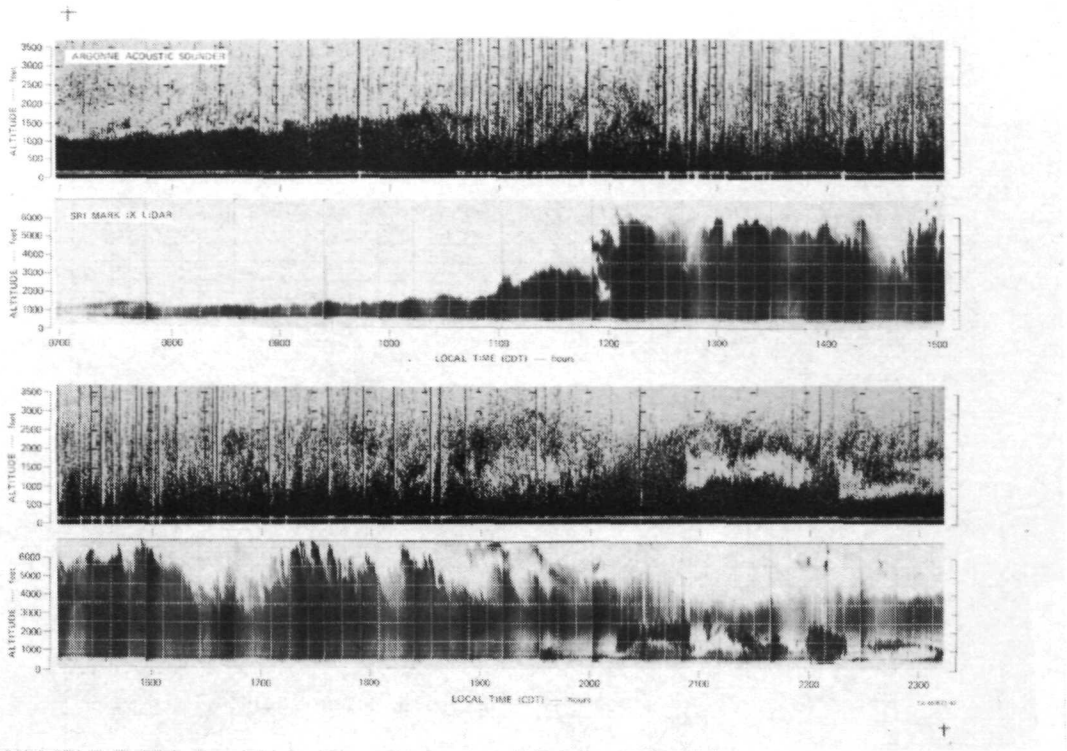

Figure 2.- Comparison of atmospheric time sections obtained by lidar and acoustic sounders at St. Louis, Missouri, on Aug. 14, 1972. Darkest areas are associated with strongest echoes. (From Russell et al., 1974)

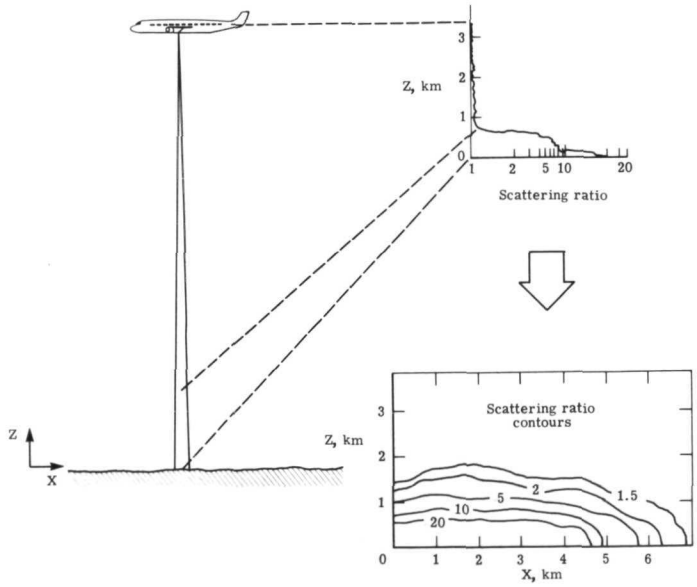

Figure 3.- Concept for observations of boundary-layer height using airborne lidar. Scattering ratio is obtained by dividing observed backscattering intensities by those expected from a dust-free atmosphere, with appropriate transmission corrections. (From Grams, 1975, courtesy National Center for Atmospheric Research)

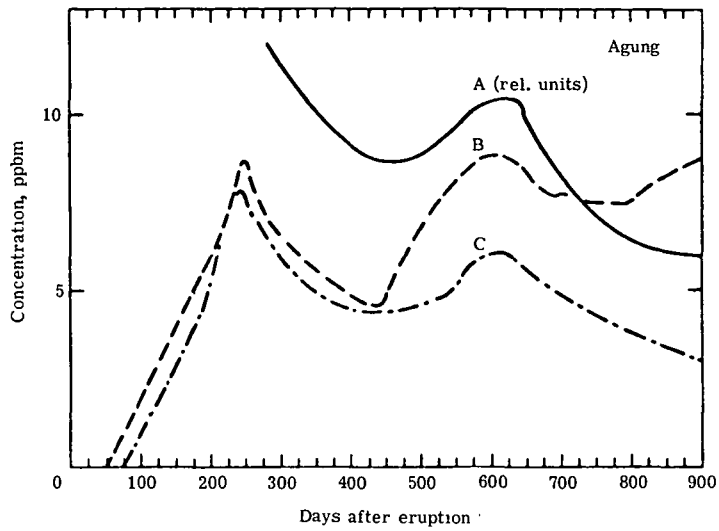

Figure 4.- Comparison between model calculations and lidar observations for temporal variation of aerosol concentration in lower stratosphere. Curve A shows lidar observations of Grams and Fiocco (1967) at the altitude of peak scattering ratio; curve B shows calculated maximum concentrations of H_2SO_4 droplets; curve C shows H_2SO_4 concentration at 18 km altitude. (From Cadle et al., 1976, courtesy American Geophysical Union)

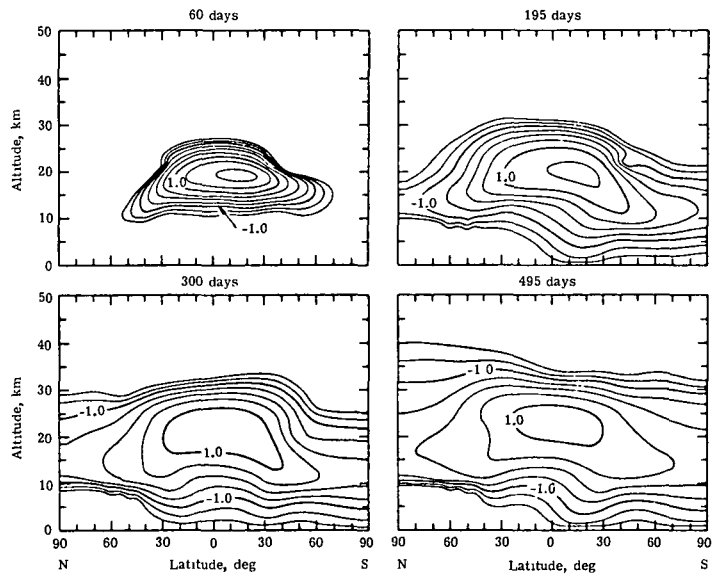

Figure 5.- Aerosol concentration isopleths (in log parts per billion by mass) from model calculations for Agung eruption. Days shown are after eruption. (From Cadle et al., 1976, courtesy American Geophysical Union)

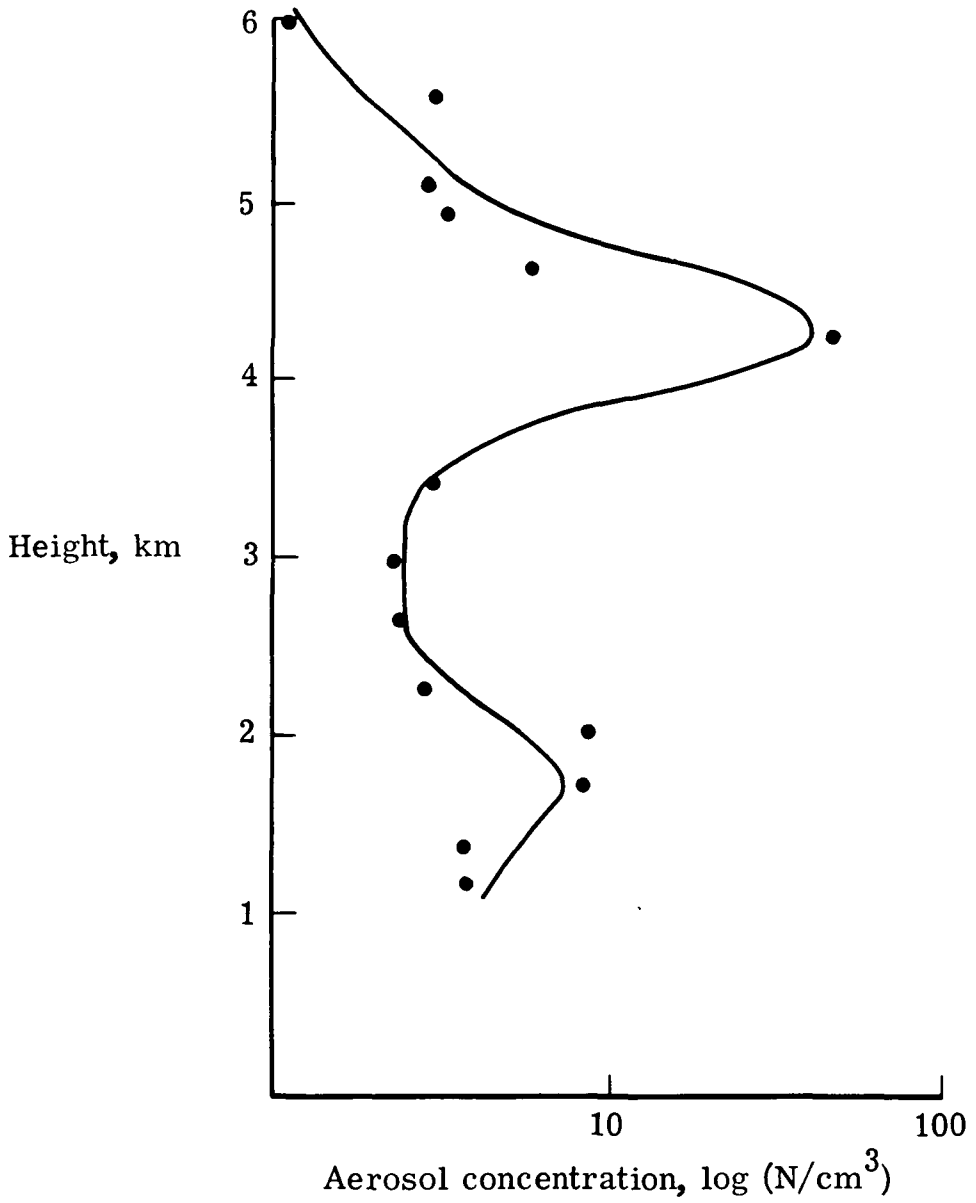

Figure 6.- Vertical distribution of aerosol particles in Saharan dust layer as observed with photoelectric particle counters during 1974 GATE program. (From Kondratyev et al., 1976)

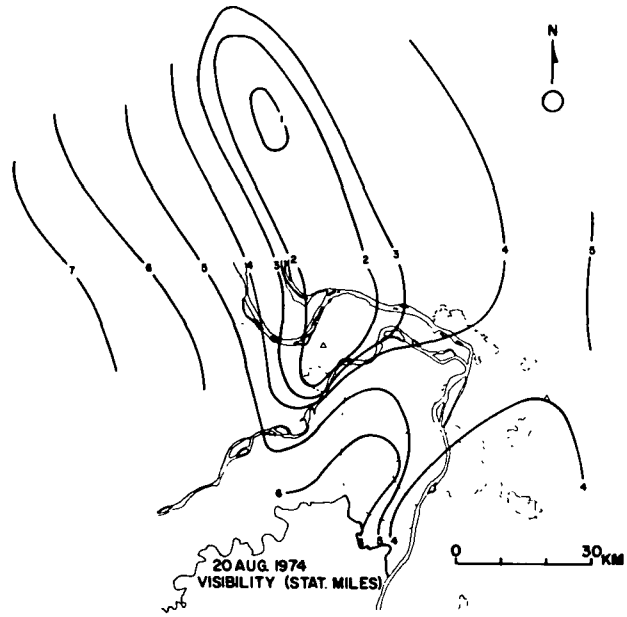

Figure 7.- Surface visibility in vicinity of St. Louis, Missouri, during METROMEX program in August 1974. (From Shea and Auer, 1978, courtesy American Meteorological Society)

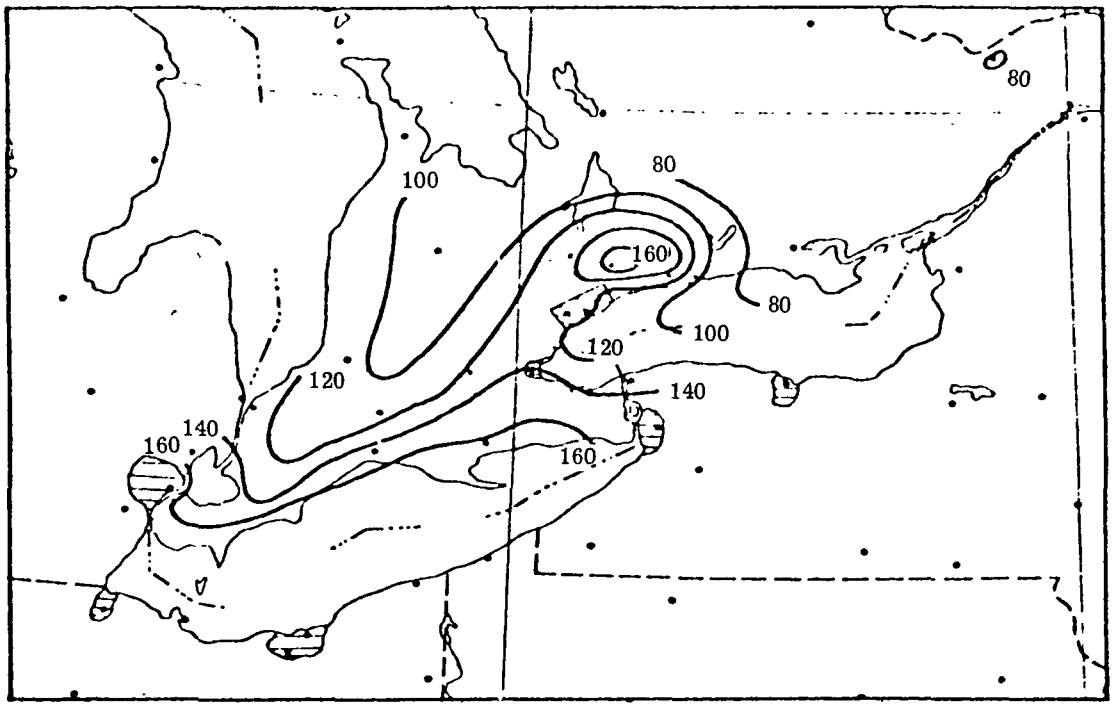

Figure 8.- Average afternoon ozone maximums (in ppb) for high ozone situations during August 1976 in southern Ontario. (From Chung, 1977, courtesy American Meteorological Society)